National Aeronautics and Space Administration

Analysis of Trim and Compressibility Effects in Extended Formation Flight

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2012 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 13-15, 2012

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Overview

- Extended formation flight
- Modeling approach
- Results
  - Mesh convergence study
  - Incompressible effects
    - Vortex position sensitivity
    - roll-trim
  - Compressible effects
    - roll-trim
- Summary
    - Current efforts

Background: Close Formations

14% reduction in heart rate when in formation (Welmerskirtch, et. al, 2001)

Background: Close Formations

Over 20% drag reduction and 18% fuel flow reduction for trailing aircraft (NASA, 2002)

Extended Formations

• ~15-40 span separation

• A safer approach to formation flight

• Can be implemented with today’s aircrafts without modification

• Up to 10% fuel flow reduction for transport aircraft*

*Pahle, Joe, “A preliminary Investigation of Formation Flight for Drag Reduction on the C-17 aircraft”

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Extended Formations

• Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

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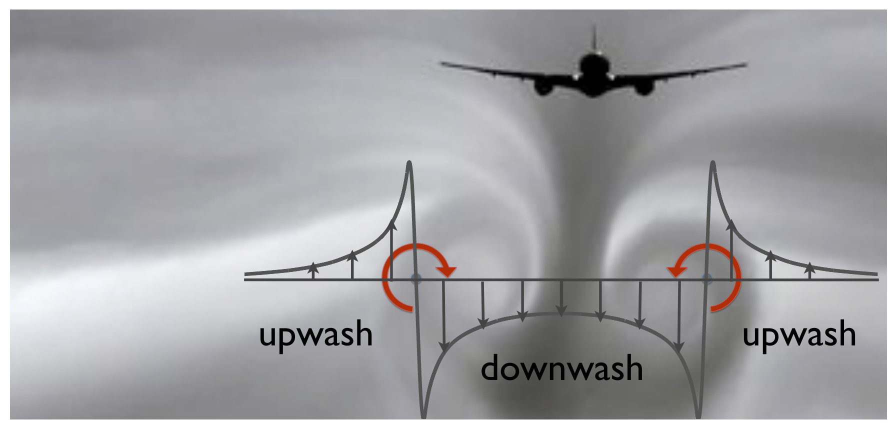
Extended Formations



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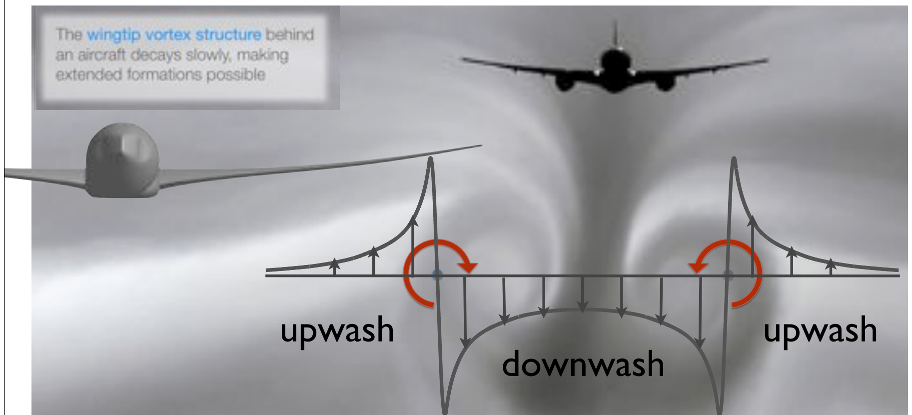
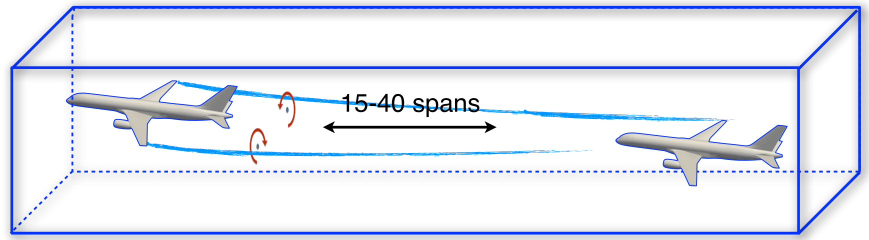
Extended Formations



• Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

Modeling

• In close formation, the trailing aircraft can influence the lead
• At 15-40 spans separation, this effect becomes negligible
• Extended formations decouple lead and follower aircraft



Lead Aircraft

Trail Aircraft

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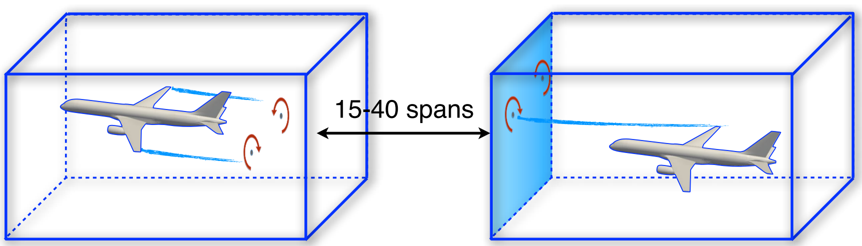
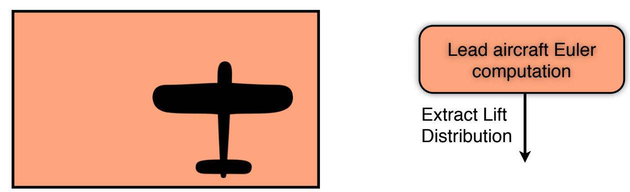


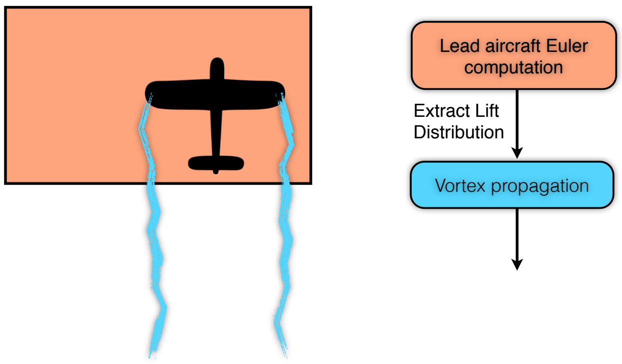
Lead Aircraft

Trail Aircraft

Modeling Approach



Modeling Approach



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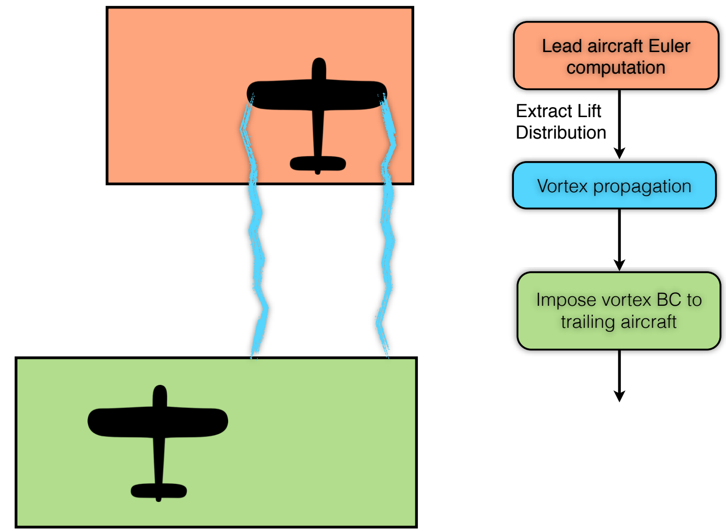

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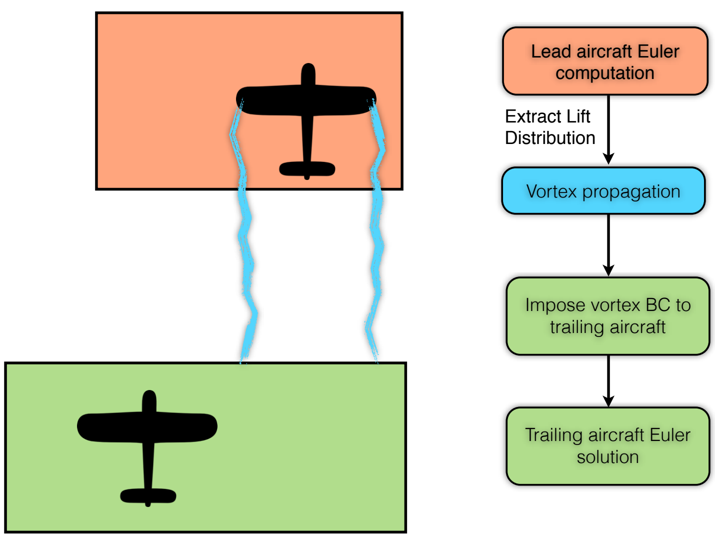

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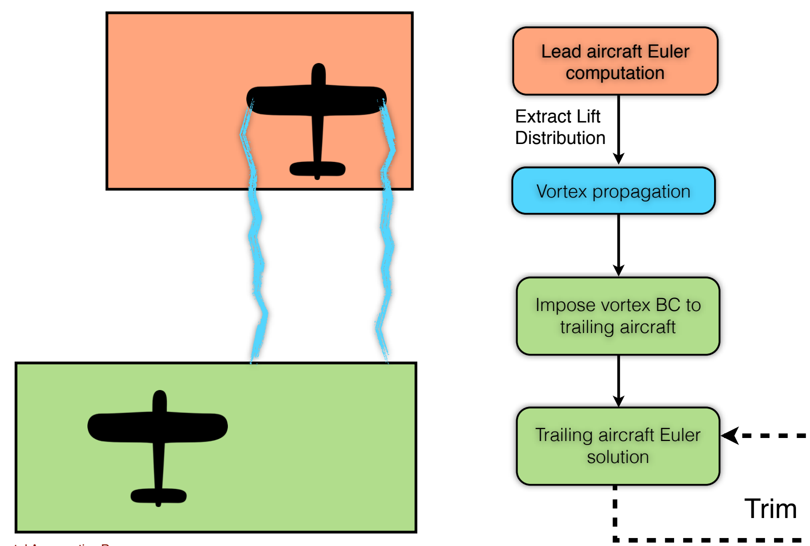
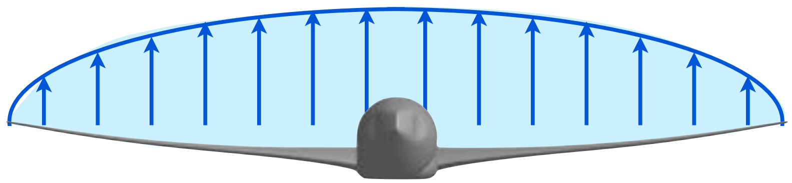
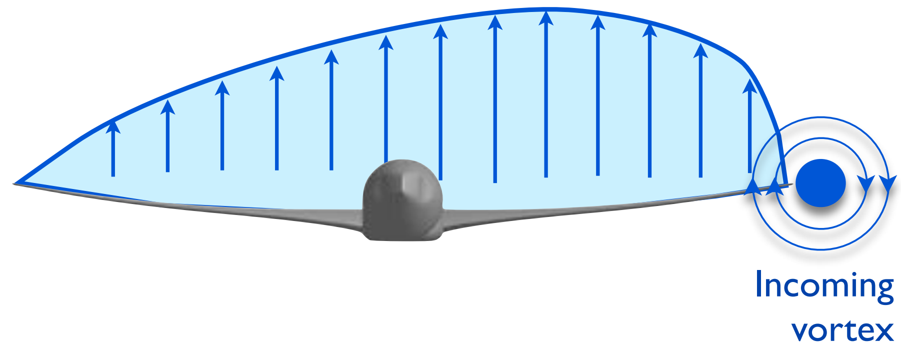


Out-of-Formation



In-Formation



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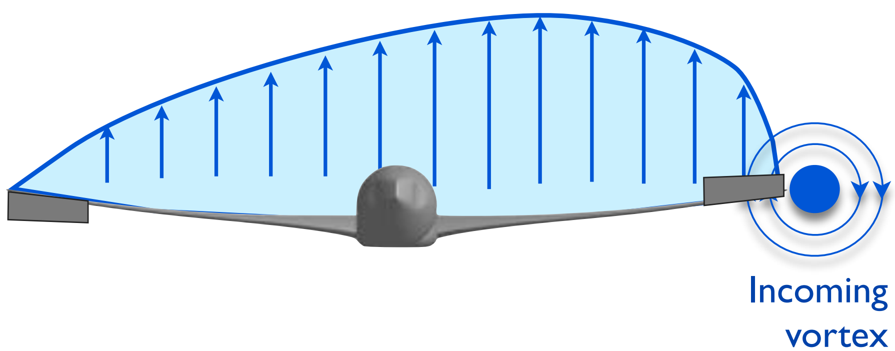

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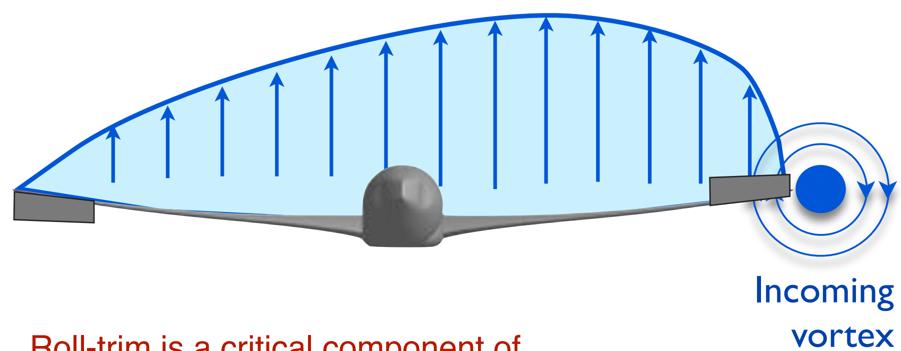


Roll-trim is a critical component of formation flying

Roll-Trim Strategy

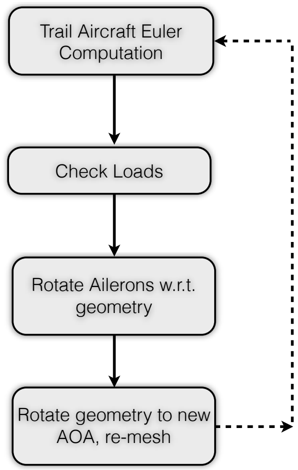
- Algorithm for trim:

(1) Compute trail A/C flow solution

(2) Check Lift & Roll tolerance

(3) Deflect ailerons if necessary (roll)

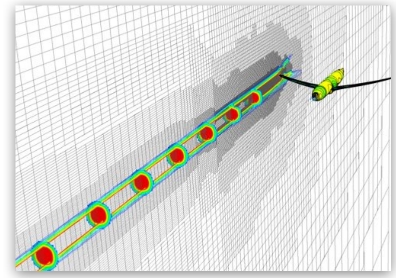
(4) Adjust AOA if necessary (lift)



Flow Analysis: Cart3D

Requirements: automatic control surface deflections, geometry re-meshing, and high-fidelity CFD solutions

- Inviscid analysis package, 3D compressible Euler equations
- Unstructured Cartesian cells with cut-cells at wall
- Adjoint-Based Mesh Adaptation
- Highly automated for parameter sweeps, geometry manipulation, and re- meshing



Flow Analysis: Objective Functional

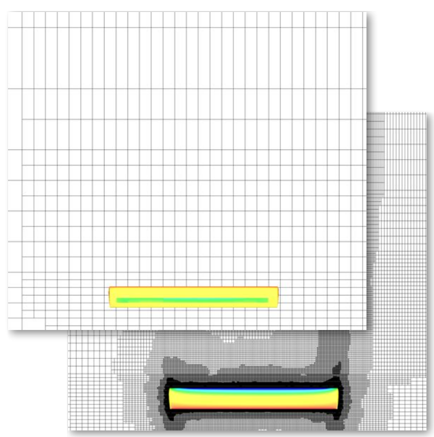
- Formation flight aims to improve induced drag at fixed lift...

$$C_{Di} = \frac{C_L^2}{\pi\, AR\, e}$$

- Span efficiency factor, e, is a natural choice

$$e = \frac{C_L^2}{\pi\, AR\, C_{Di}}$$

Initial Mesh (100k cells)



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$$e = \frac{C_L^2}{\pi\, AR\, C_{Di}}$$

$C_D \sim 0.008$

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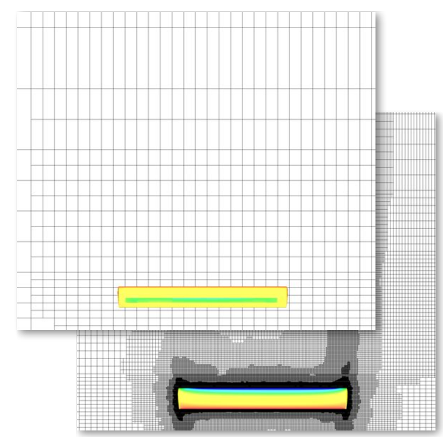

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Expensive to converge due to drag sensitivity

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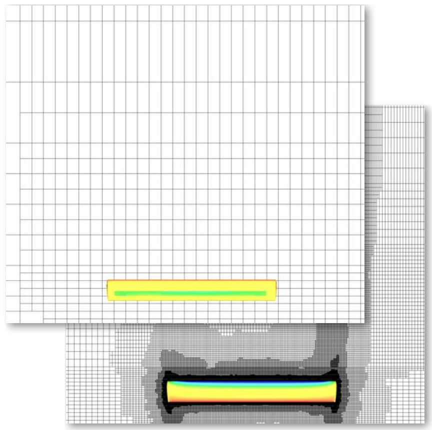

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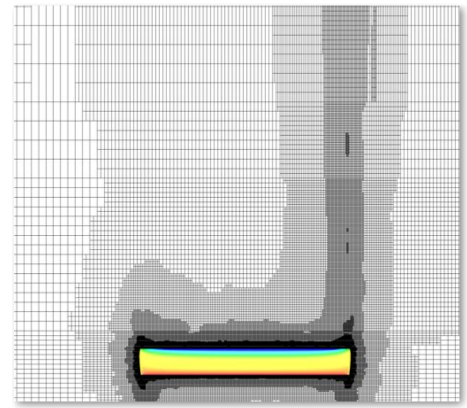
Expensive to converge due to drag sensitivity

Final mesh (20 mil. cells)



Results Outline

- Mesh convergence study
- Incompressible Effects
  - roll-trim
  - Vortex position sensitivity
- Compressible Effects
  - roll-trim

Formation flight metric

$$\text{drag fraction} = \frac{\sum D_{\text{in formation}}}{\sum D_{\text{out formation}}}$$

- Provides a measure for overall drag savings of the formation
- Focus on 2-aircraft echelon formations...

$$\text{drag fraction} = \frac{D_{\text{lead}} + D_{\text{trail}}}{2 D_{\text{lead}}}$$

Ex.: a drag fraction of 0.9 represents a 10% drag savings in formation flight

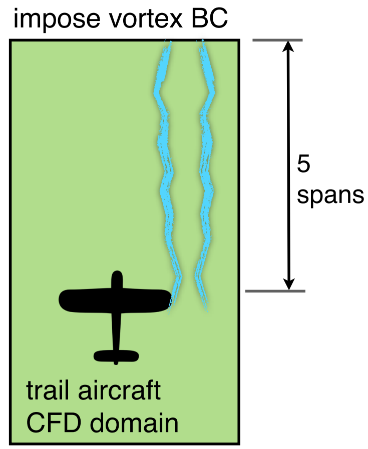
Results: Vortex in empty domain

Flow conditions

- Mach = 0.5
- CL (lead A/C) = 0.55
- Objective Function: Integrated pressure at 5 spans from inflow

Goal

- Verify mesh convergence of vortex in absence of geometry



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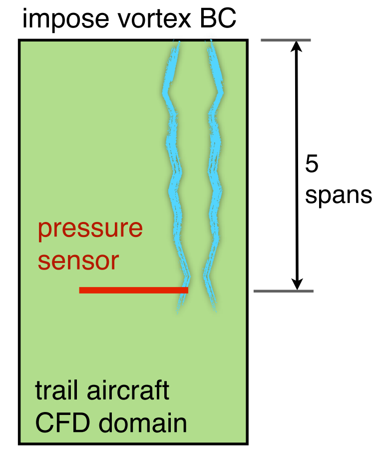

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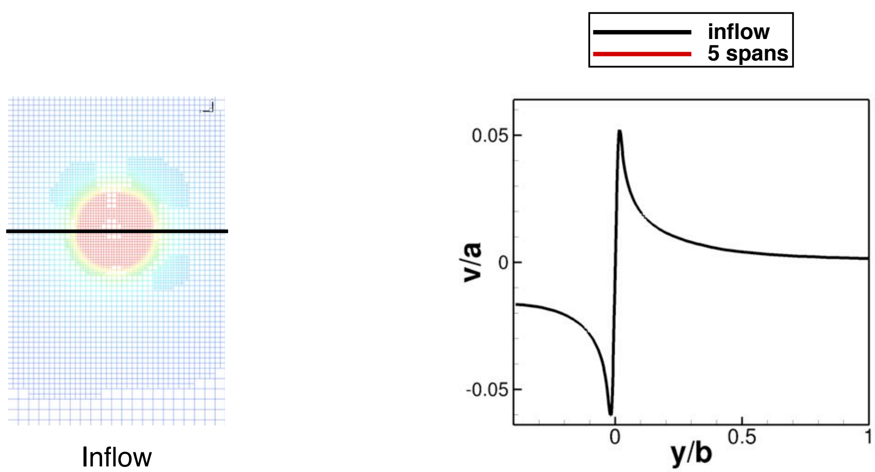

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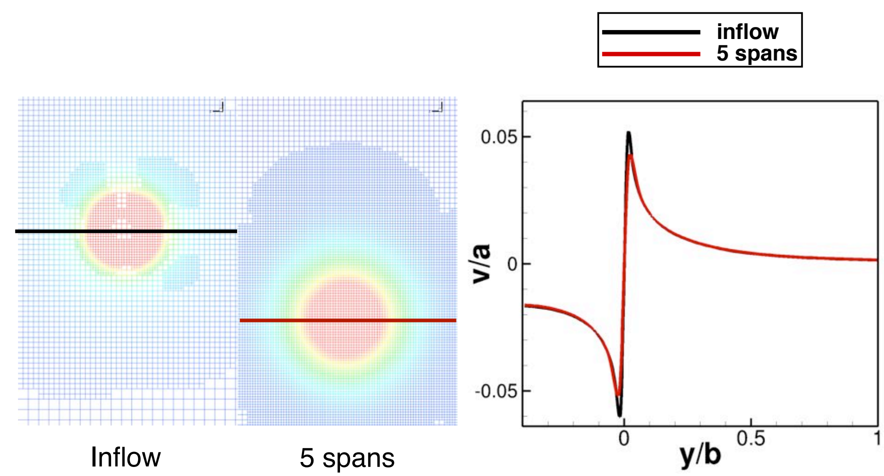

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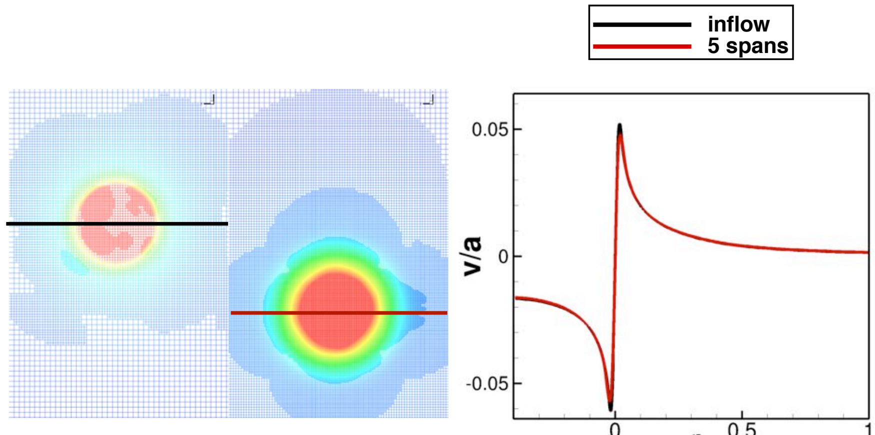
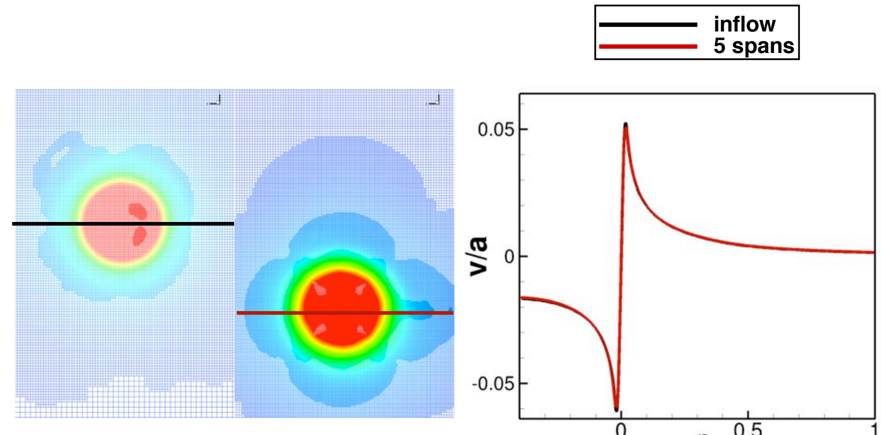


Inflow   5 spans

Results: Vortex in empty domain

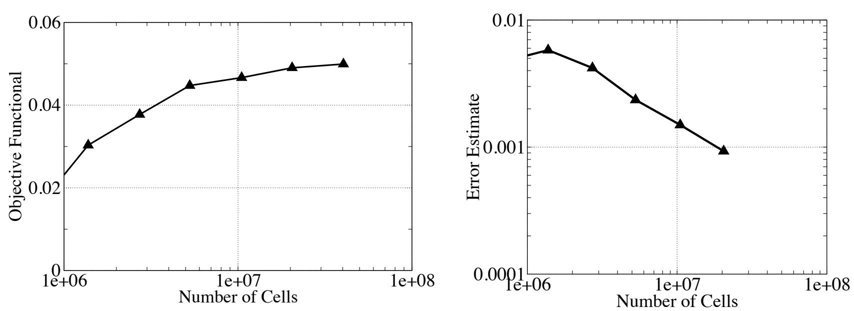


Inflow   5 spans

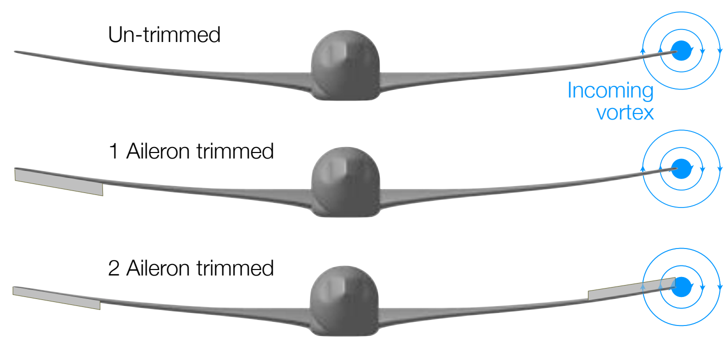
Results: Vortex in empty domain

Mach = 0.5

- Objective functional: integrated pressure 5 spans downstream



Results: Trimming Configurations



- un-trimmed (baseline) configuration contains no ailerons
- 1-aileron deflected; increases lift on out-of-vortex wing
- 2-aileron deflected; trims in conventional manner

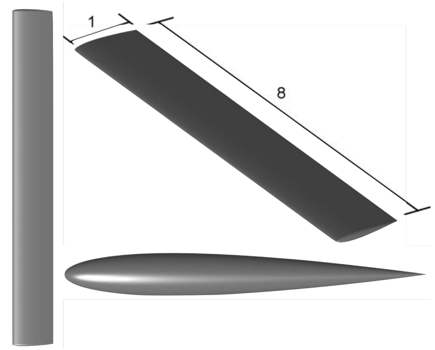
Results: Simple Wing

Geometry

- Sub-sonic straight wing w/ NACA 0012 sections

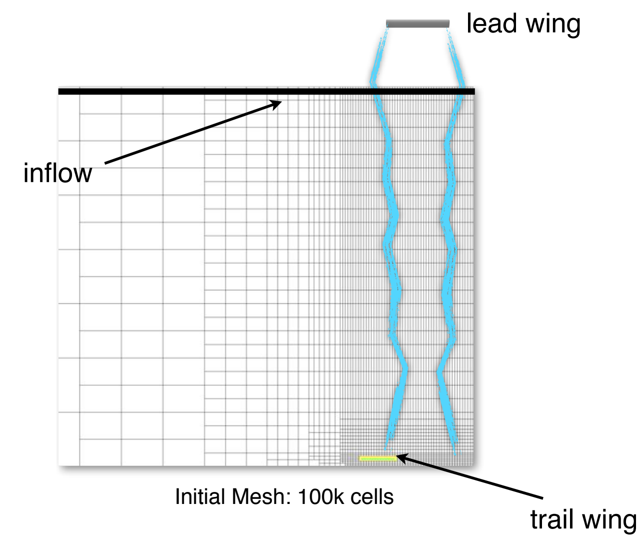
Goals

- Quantify/Verify incompressible formation flight drag savings
- Roll-trim effects
- Determine trail A/C position sensitivity



Geometry	C_L	M_∞	AR	$S_{ref}(ft^2)$
NACA 0012 Wing	0.55	0.5	8	8

Results: Simple Wing



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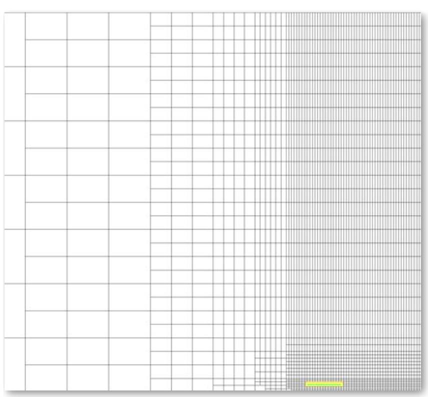
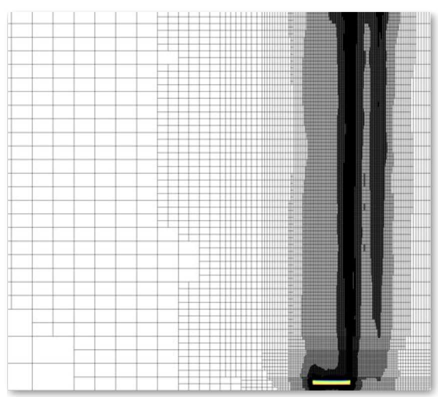
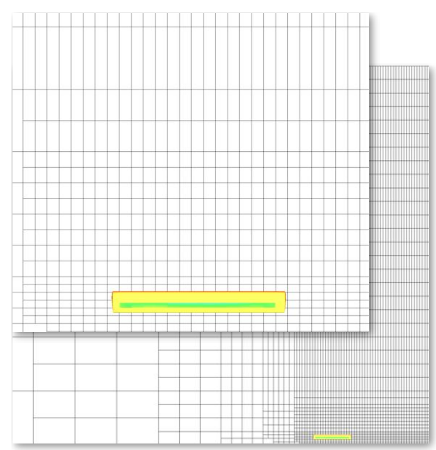


Initial Mesh: 100k cells



Final Mesh: 20 Mil. cells

Results: Simple Wing



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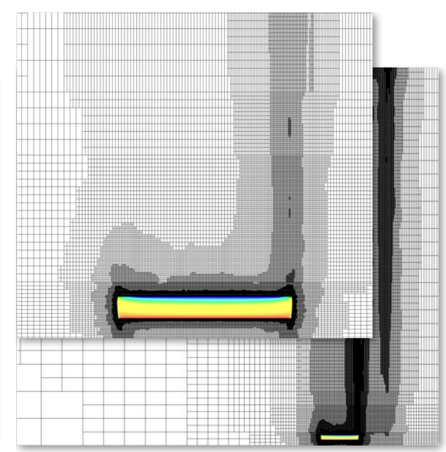

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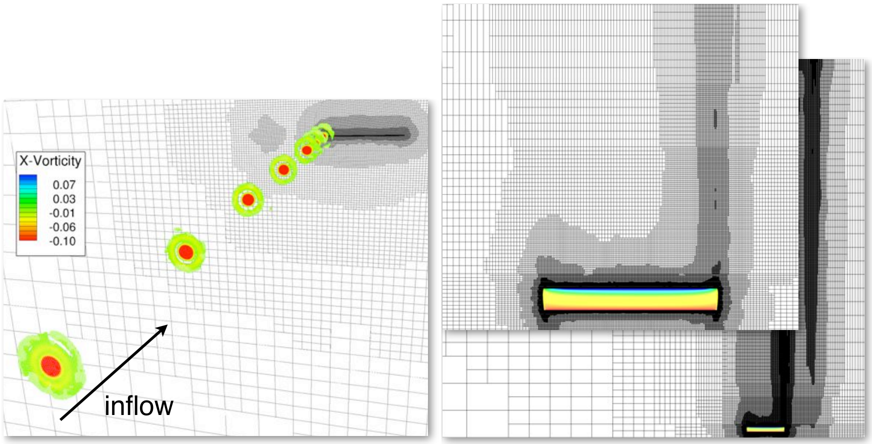

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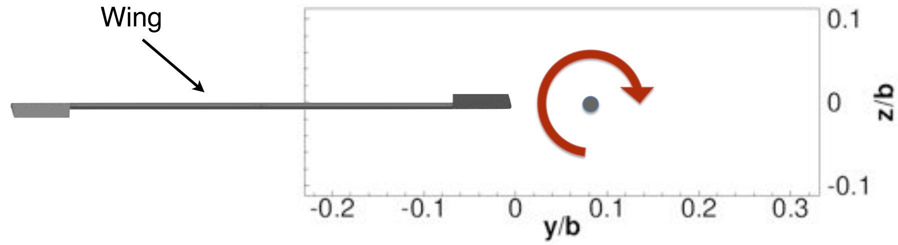
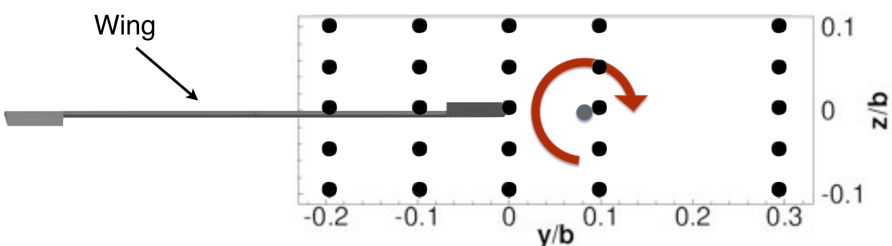
Results: Vortex Position Sensitivity



*View behind wing facing upstream

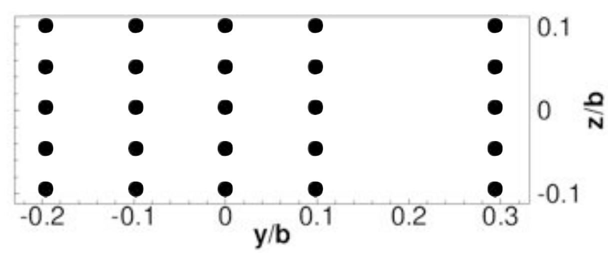
Results: Vortex Position Sensitivity



● CFD point

*View behind wing facing upstream

Results: Vortex Position Sensitivity



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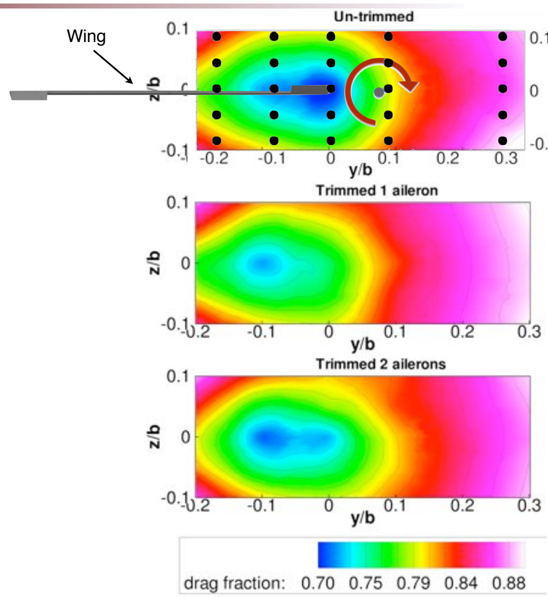
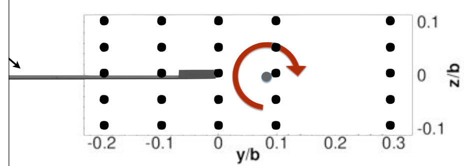
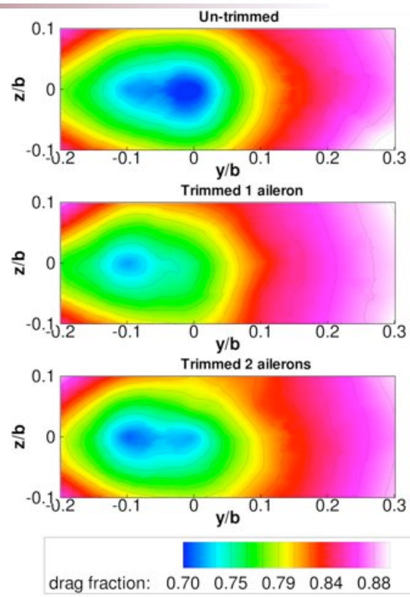


Results: Vortex Position Sensitivity

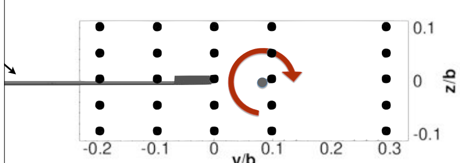
- Optimal vortex location migrates inboard w/ trim
- 2-aileron outperforms 1-aileron trim
- 3-5% decrease in drag fraction for 2-aileron

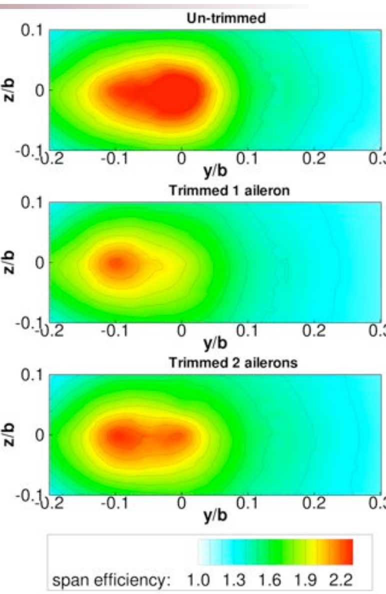




Results: Vortex Position Sensitivity

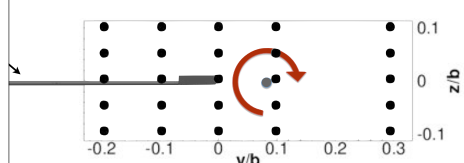
- un-trimmed, optimal span efficiency ~2.2 @ wingtip
- Optimal vortex location migrates inboard w/ trim
- 2-aileron trimmed outperforms 1-aileron

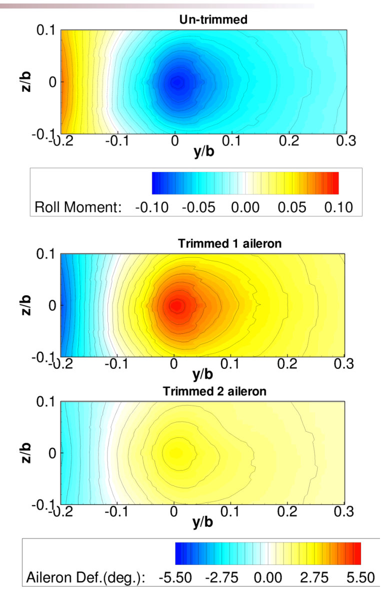




Results: Vortex Position Sensitivity

- Largest induced rolling moments occur at wingtip and 20% overlap
- Near 10% overlap, no induced rolling moments, yet close to optimal drag savings





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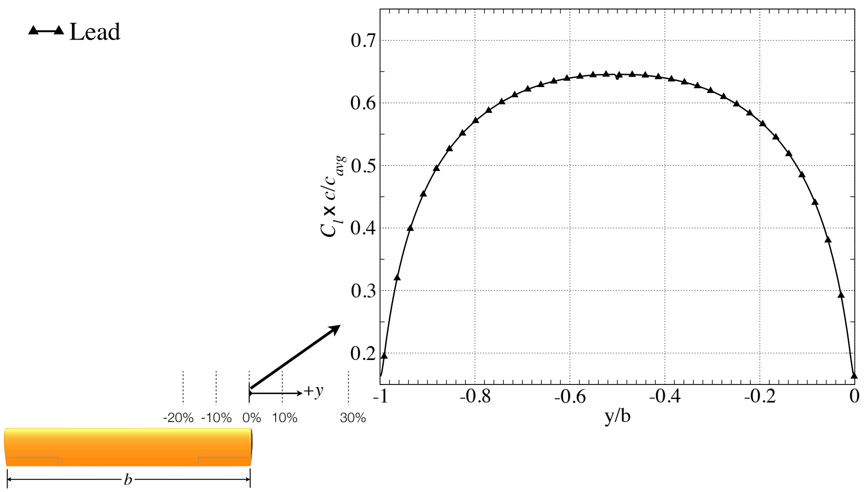

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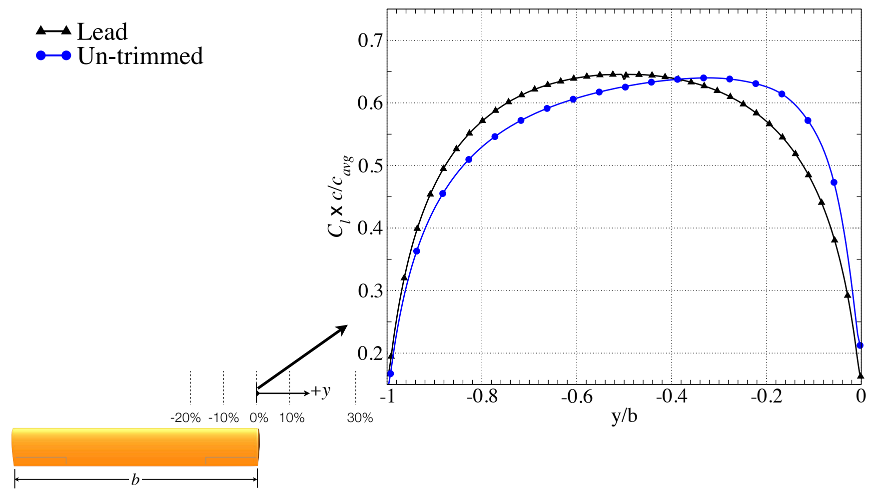

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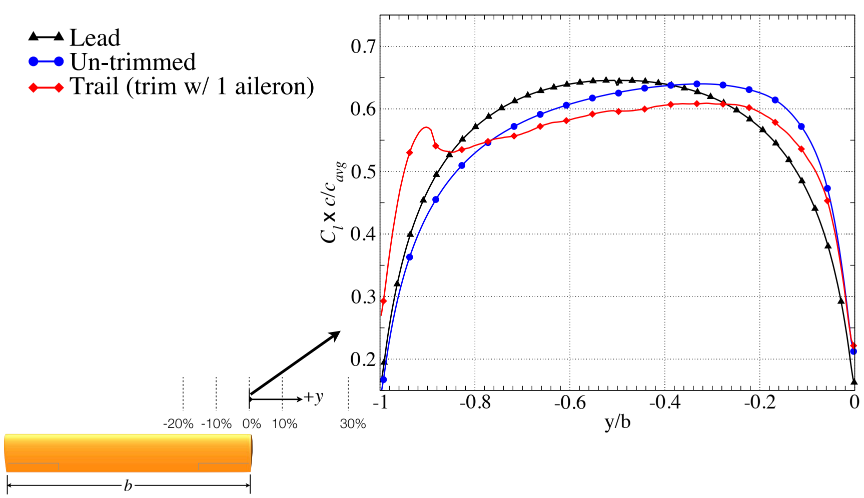

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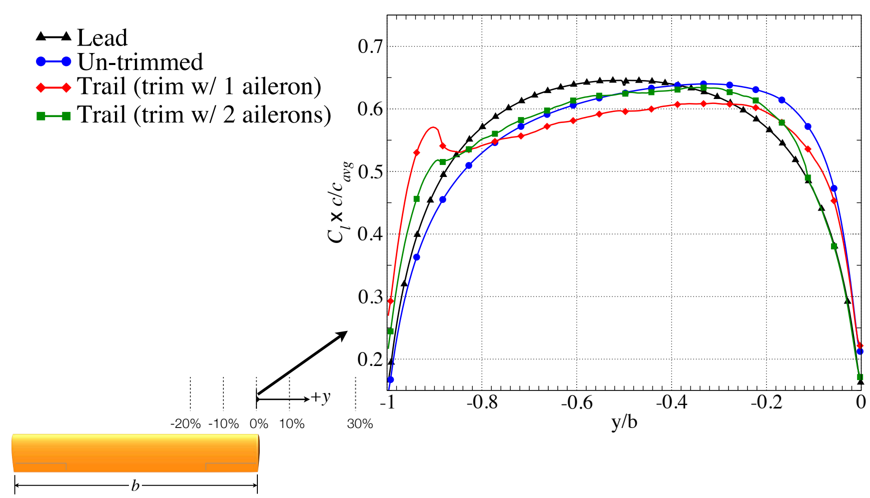

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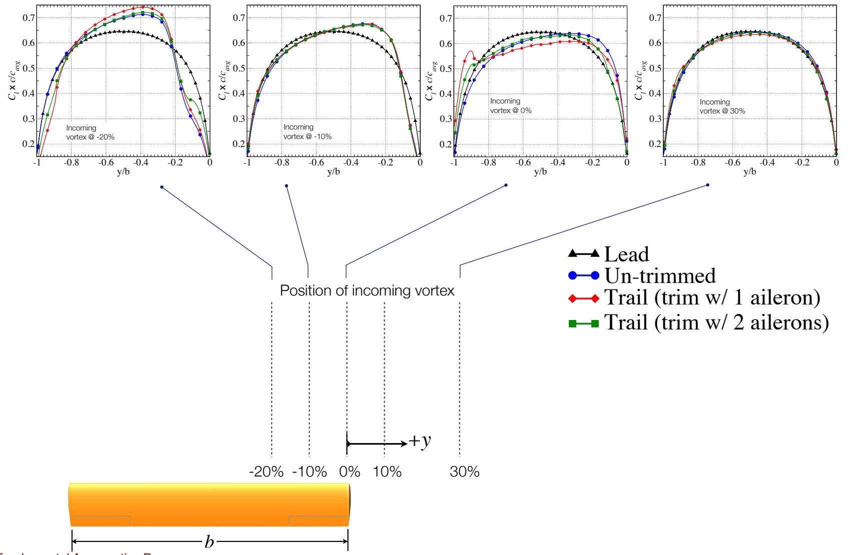


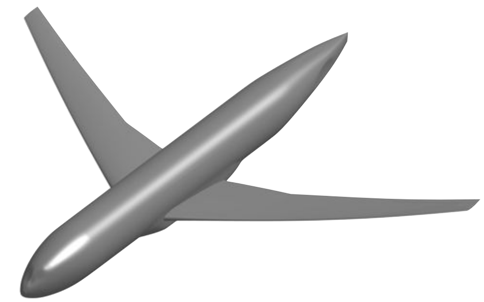
Results: Common Research Model

Geometry

- Modified CRM from 4th AIAA Drag Prediction Workshop*

Goals

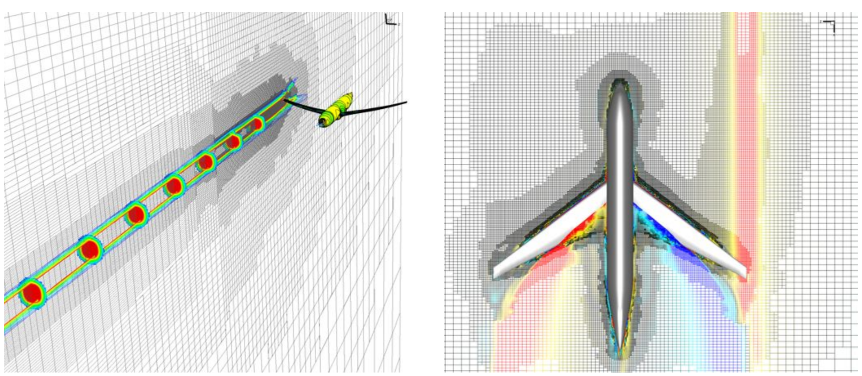
- Quantify compressible formation flight drag savings
- Determine roll-trim effects on more realistic wing/body geometry



Geometry	C_L	M_∞	AR	$S_{ref}(ft^2)$
CRM	0.5	0.83	9	4130

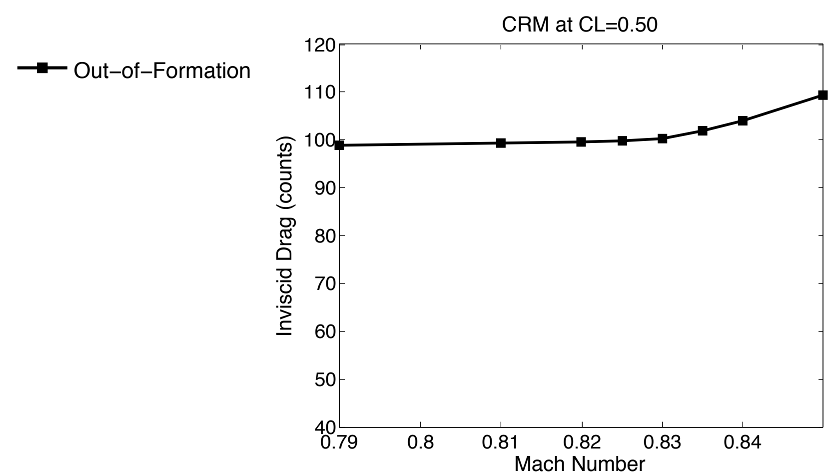
*Vassberg, J. C.,et al. Development of a Common Research Model for Applied CFD Validation Studies, AIAA Applied Aerodynamics Conference, AIAA 2008-6919, August 2008.

Results: CRM



Final Mesh: 40 Mil. cells

Results: CRM



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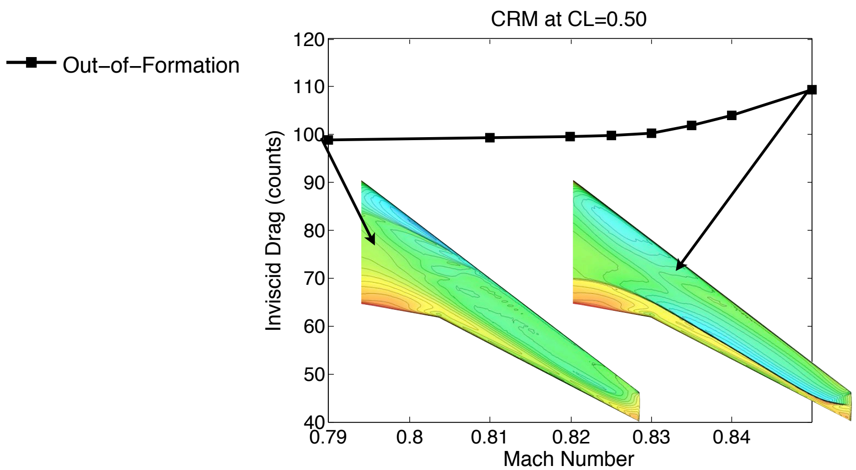

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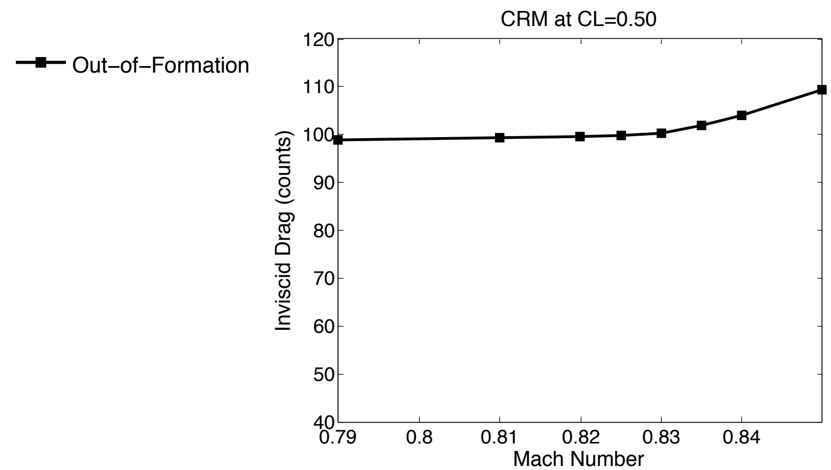

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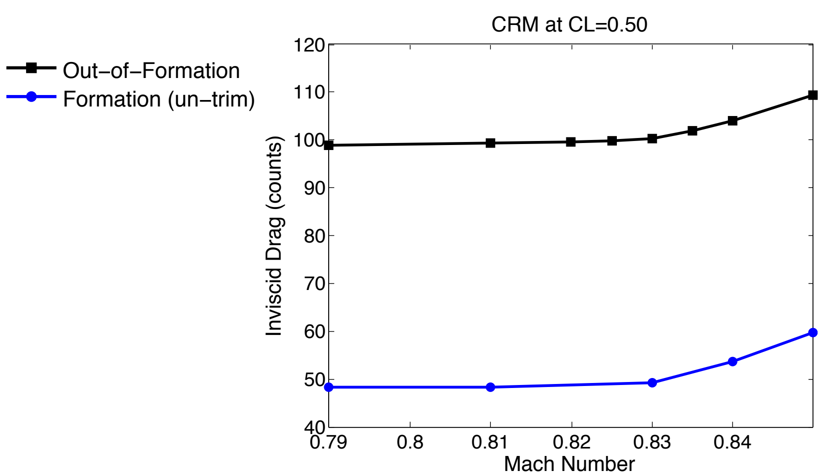

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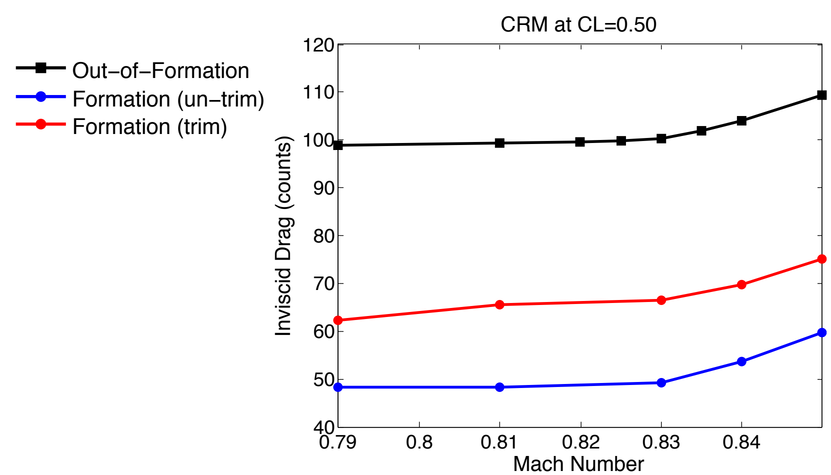
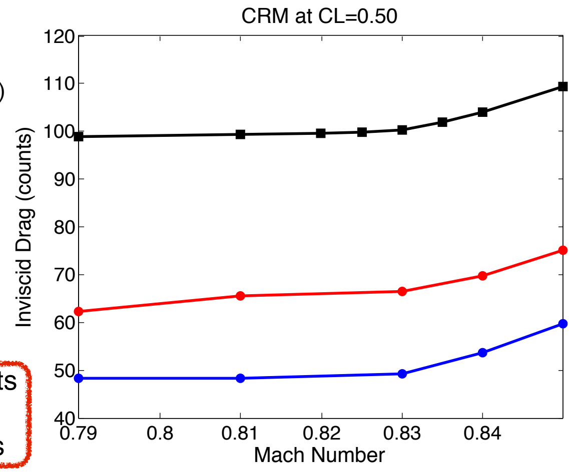
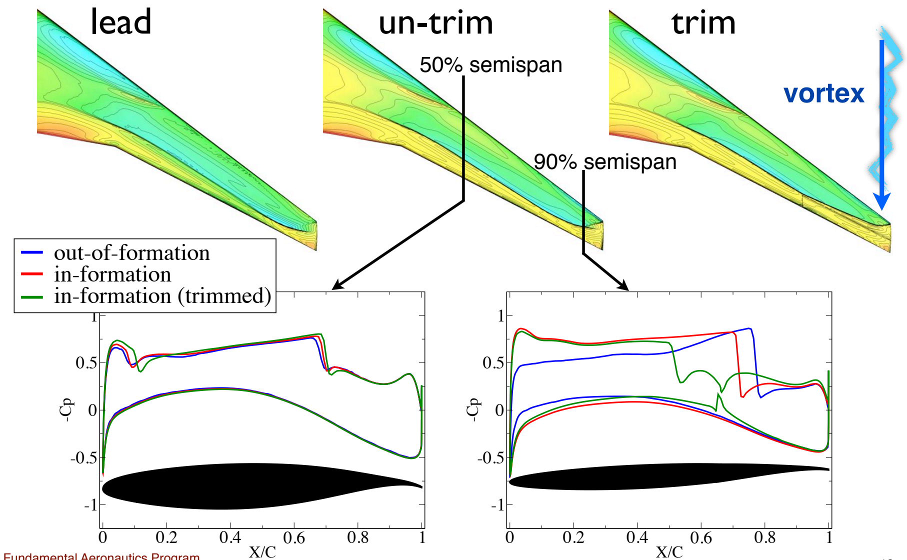


Results: CRM

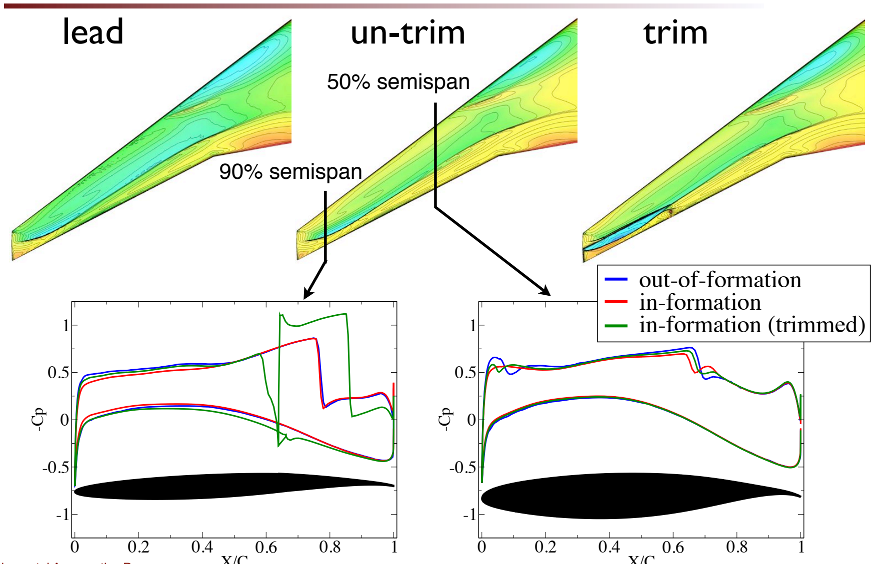


Transonic trim accounts for ~20% erosion of formation drag savings

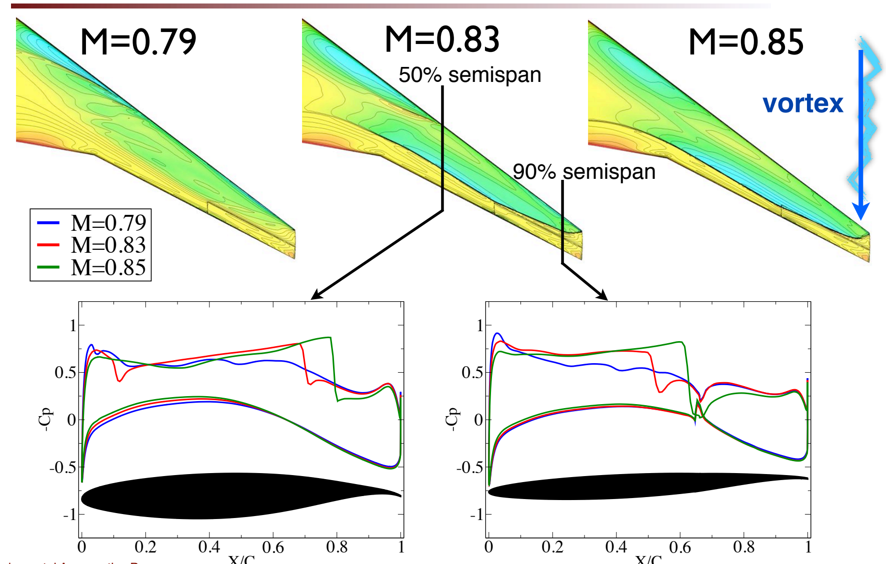
CRM, Mach = 0.83



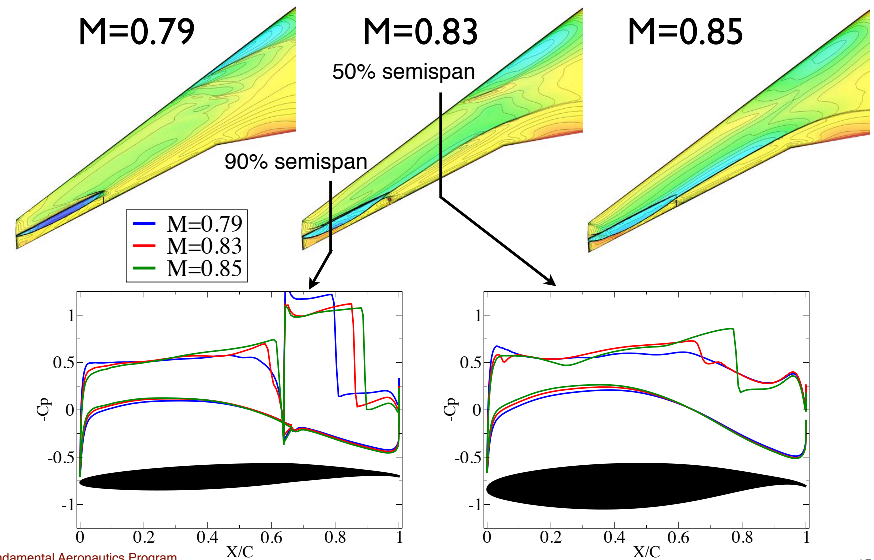
CRM, Mach = 0.83



CRM, In-Formation, trimmed



CRM, In-Formation, trimmed



Summary

- Performed relevant verification for vortex boundary condition
- Developed methodology for evaluating formation flight benefits for 2-aircraft echelon formations
- Developed quantitative benefit maps for trail aircraft positioning
- Evaluated erosion of formation flight benefits as a result of trim and compressibility

Open Issues

- Complete benefits map for summer conference
- Extend analysis to > 2 aircraft formations
- Effects of heterogenous aircrafts in formation
- Deliver analytic drag model for formation flight including trim/ compressibility for use in NAS models

Wake Propagation Model

Augmented Betz Method*

- Far-field conservation method
- Experimental core-size data
- LES vortex decay rates

Assumptions

- Viscous effects neglected during rollup
- All vorticity from lead is axis-symmetrically rolled-up into 2 vortices

Governing Equations:

continuity:

$$\frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

vorticity:

$$\frac{\partial \zeta}{\partial t} + u_y \frac{\partial \zeta}{\partial y} + u_z \frac{\partial \zeta}{\partial z} = \nu \left(\frac{\partial^2 \zeta}{\partial y^2} + \frac{\partial^2 \zeta}{\partial z^2} \right)$$

$$\left(\text{where } \zeta = \frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z} \right)$$

Time Invariants:

$$\Gamma_0 = \int \zeta dA$$

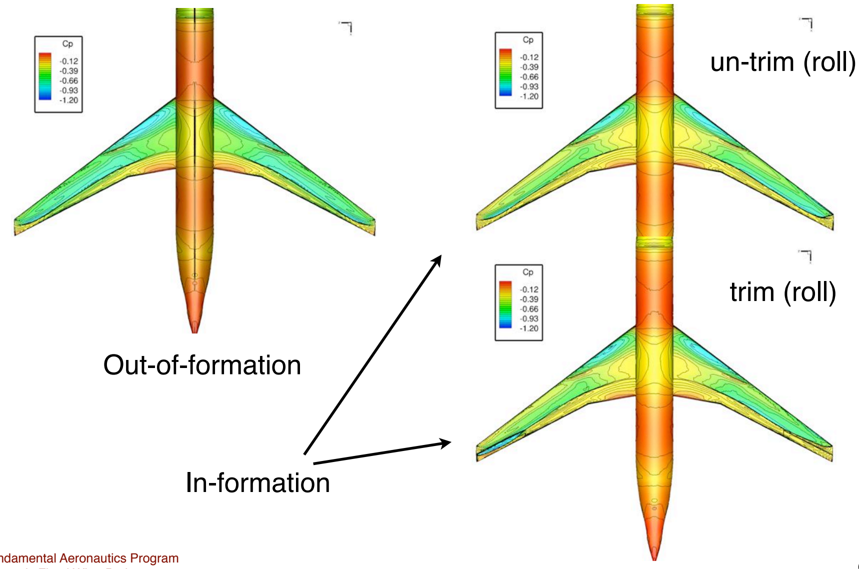
$$\Gamma_y = \int y\zeta dA$$

$$\Gamma_z = \int z\zeta dA$$

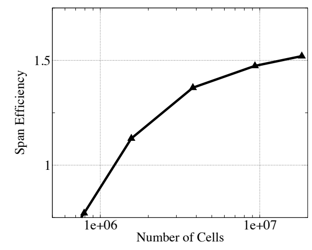
$$\Gamma_r = \int (y^2 + z^2)\zeta dA$$

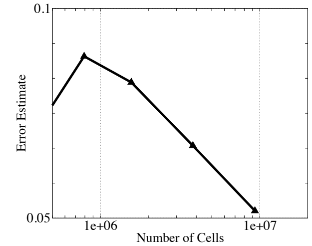
*Ning, Andrew, Aerodynamic Performance of Extended Formation Flight, Journal of Aircraft, Vol. 48, No. 3, May-June 2011

Results: CRM at M=0.83



Results: Simple Wing





$$e = \frac{C_L^2}{\pi \, AR \, C_{Di}}$$